DYNAMICS OF OCEANIC MOTIONS

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LONG-TERM GOALS

This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: knowledge of realistic regional processes and general physical and physical/acoustical processes; and to the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.

OBJECTIVES

General objectives are:

(I) To determine for the coastal and/or coupled deep ocean the multiscale processes which occur:

- i) in the physical response to external and boundary forcings and via internal dynamical processes;
- ii) in the physical-biological-chemical interactions which control productivity and provide connectivity and isolation mechanisms for (sub) regional ecosystems;
- iii) in the physical-acoustical interactions which influence acoustic propagation and tomographic inversions.

(II) To nowcast, forecast and simulate with data assimilation realistic oceanic fields with (sub) mesoscale resolution over large scale domains and to understand the essential dynamics controlling forecasts and regional predictability. Specific objectives include:

- i) Northwest Atlantic shelf seas studies with atmospheric and river flux;
- ii) Mediterranean studies in the Sicily Straits and the eastern basin;
- iii) extension and application of our balance of terms scheme (EVA) to multiscale, interdisciplinary fields with data assimilation;
- iv) extension and application of our hybrid ESSE data assimilation scheme to interdisciplinary fields and parameter estimation; and,
- v) regional predictability studies.

APPROACH

Field estimates are obtained via the melding of data and dynamics in a modular, flexible forecast and simulation system (Harvard Ocean Prediction System - HOPS). Dynamically adjusted fields are used in detailed physical, acoustical and biogeochemical/ecosystem process analyses based on the balance of terms of the dynamical equations. Data assimilation is carried out for dynamical adjustment, dynamical interpolation and data-driven simulations. Assimilation algorithms include a robust optimal interpolation scheme and a hybrid method for evolving forecast errors based on an EOF representation of the dominant error subspace and an ensemble forecast error estimate (Error Subspace Statistical Estimation - ESSE). The pre-treatment of data before assimilation,via structured data models (e.g. feature models), maximizes the data information content. A sequence of two-way nested model domains and nested observational strategies are used to establish accurate representations of multi-scale processes and interactions. Theoretical, GFD, and data driven

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simulations are utilized with feedbacks.

WORK COMPLETED

ESSE - The Error Subspace Statistical Assimilation (ESSE) system has been further tested and enhanced. The system has been designed for use in multivariate objective analysis, forecast with assimilation (filtering) and data-driven simulations with initial condition estimations (smoothing). Several studies and comparisons were carried out. Novel concepts related to recent progress in weather forecasting and turbulent studies were introduced: e.g. generalized Optimal Perturbations and Stochastic Optimals, Data Optimals and Model Error Optimals. An adaptive component of ESSE was derived. Associated efficient mathematical systems for continuous-time learning of the dominant eigendecomposition of covariances were derived. These dominant covariance trackers were used to define efficient systems for continuous minimum error variance filtering via adaptive ESSE.

Interdisciplinary modeling - Schemes for physical-biological field estimation and data assimilation have been finalized. Simulations with and without physical and/or biological data assimilation, Gulf Stream rings, and surface wind forcing were carried out to examine sensitivity to each of these. Our best estimate simulation of the Gulf Stream during BioSYNOP (Sep-Oct 1988) has been completed.

Software - Several open boundary conditions (OBC) in HOPS model code were corrected and new ones implemented. Some OBC were determined inadequate from simple principles and new approaches were derived. One combines OBC formulations via a minimum error variance based on a flow-type dependent uncertainty assigned to each OBC estimate. Other improvements involve Shapiro filtering, coastal and bottom numerical boundary layers. A stochastic PE error model was also derived and implemented in HOPS. The objective analysis software has been extended to include biological variables. Codes and procedures for obtaining realtime forecasts of meteorological variables and determining surface forcing fluxes for the model (net heat flux, net water flux, momentum flux, shortwave radiation flux), have been improved.

Feature models - Temperature and salinity based feature models have been extended to include dynamical information in the blending of synoptic data, fronts and rings. Velocity-based feature models of the Gulf Stream now includes the warm core.

Biology - The general theory of advective effects on biological dynamics has been extended to include injection events, Michaelis-Menten non-linear interactions, light limitation and surface mixed layer processes. Evidence based on modeling studies and observations indicates that the vertical flux induced by the dynamics of mesoscale eddies is sufficient to balance the nutrient budget in the Sargasso Sea and may be the dominant mode of nutrient transport in the open ocean.

RESULTS

Dynamical circulation studies of the data from the Strait of Sicily collected during 1994-1996 indicated the presence of newly identified features: Adventure Bank Vortex (ABV), Maltese Channel Crest (MCC) and Ionian Shelf Break Vortex (IBV). A schematic water mass model for the region was developed. The adaptive ESSE system was applied and compared in real-time to the OI scheme for a 10-day period within the NATO naval operation Rapid Response 96 in the Strait of Sicily. Real-time ocean field error forecasts were issued. Evaluating the forecast-data misfits at the *in situ* observation points around the IBV region shows that the ESSE forecasts are, on average, 20% better than OI forecasts. Qualitative performance analysis against SST over the complete domain indicate higher ESSE improvement factors. In this region, the nonlinear ESSE scheme is 1000 times computationally cheaper than classic linear full-covariance methods (e.g. Kalman Filters). The Error Subspace forecast also allows for the determination of the forecast Data Optimals, i.e. the most desired and least expensive future observation patterns within the available observation networks. Several of the 3D multivariate processes responsible for the August-

September variabilities of the ABV, MCC, IBV, and Ionian shelfbreak temperature and salinity fronts were decomposed and discussed within the PE dynamics framework. It was shown that the ESSE system without assimilation continuously decomposes, organizes and tracks the most energetic nonlinear ocean variability.

The spreading of the Levantine Intermediate Water (LIW) was investigated via ESSE. The data-driven simulations suggest that several phenomena interacting on multiple scales are responsible for the dispersal. The LIW predominantly spreads in a rotating motion along sloping isopycnals from the centers of meandering cyclonic gyres into adjacent jets and anticyclonic gyres, which further advect the intermediate water. The source of LIW in the spring is both internal mixing and surface forcing. From the assimilation point of view, a stochastic PE noise is used to model surface dynamical errors.

Assimilation of physical or biological data assimilation alone causes a misalignment between the physical and biological fronts, which results in enhanced cross-frontal exchange of biological quantities and consequently spuriously enhanced biological productivity. Simultaneous physical and biological data assimilation are necessary. Compatable physical and biological fields are required for assimilation. We have developed a scheme for constructing compatable synoptic physical and biological fields, which involves, in sequence: (a) a first guess parameterization and/or climatological initialization of physical features, (b) objective analysis of synoptic physical data into these fields, (c) dynamical adjustment of the physical fields, including ageostrophic and vertical velocities, by running for several days in a primitive equation model, (d) a first guess initialization of the biological fields, typically through data-derived correlations with physical properties (e.g. temperature), (e) objective analysis of synoptic biological data into these fields, (f) dynamical adjustment of the biological fields with each other, the biological model parameters and the physical transports by running the ecosystem model for several days with fixed velocity fields. At the conclusion of this process, the physical and biological fields are ready to be used as a coupled system.

While Gulf Stream meandering leads to upwelling and downwelling along the Gulf Stream, the net effects largely cancel out regarding the net vertical transport of biological quantities and biological enhancement. Rings interacting with the Gulf Stream can pull out water laterally from these upwelling or downwelling zones, significantly enhancing the net vertical transport of biological quantities. Synoptic winds can force cross-frontal flow and therefore enhance the exchange of plankton across the Gulf Stream. For nitrate, it is the effect of wind speed on mixed layer depth that influences mixed layer concentrations.

IMPACT/APPLICATIONS

The important ESSE concept is that the evolution of 3D multivariate forecast variability and error can be efficiently described by a small number of adequate functions (e.g. error EOFs). The most energetic variability and error fields are expected to evolve in limited subspaces. In general, ESSE is useful for a wide range of applications, including nonlinear field and error forecasting, finding numerical instabilities, performing predictability studies, objective analyses, data-driven simulations, adaptive sampling and parameter estimation.

We now have a feasible methodology for biological field estimation and data assimilation, that is also applicable to satellite-derived data. An important implication is that the assimilation of ocean color data into physical-biological models should be concurrent with the assimilation of SST data. This is not only because the SST data can be used to fill in the gaps of the color data, but especially because the biological features need corresponding physical features to support them. Our methodology, in conjunction with the bio-optical modeling research being carried out in a related project, is also useful for assimilating ship-derived physical and biological data, and thus in ground-truthing satellite-based measurements.

Our improved understanding of the biological response to physical processes in fronts and mesoscale patches will provide useful to the basic research and applied research scientific communities.

Real-time regional forecasting research results are directly applicable to the design of ocean prediction and monitoring systems for: naval operations; research operations; the efficient environmental management of, and commercial operations within, a multi-use Exclusive Economic Zone; interdisciplinary global change research.

TRANSITIONS

Definitive results are passed to Harvard 6.2 research   Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS) . These include, but are not limited to, the ESSE data assimilation methodology, improvements to the dynamical model upper ocean.

RELATED PROJECTS

This project is closely related to other Harvard projects, including: National Ocean Partnership Program in the development of the scientific and technical conceptual basis of a generally applicable Littoral Ocean Observing and Predictive System (LOOPS) with Johns Hopkins University (APL), MIT - AUV Lab., MIT - Sea Grant, MIT - Ocean Engineering, Naval Underwater Warfare Center, National Marine Fisheries Service, Raytheon, Tracor Applied Science, Univ. of California - Santa Barbara, Univ. of Massachusetts - Dartmouth; research towards the construction of an Advanced Fisheries Management and Information System (AFMIS) with UMass-Dartmouth (Prof. B. Rothschild); BIO-OPTICS research (Dr. Jeffrey Dusenberry); the Shelfbreak PRIMER and Harvard 6.2 research mentioned previously. In addition, important collaborations are ongoing with NRL Stennis (Dr. A. Warn-Varnas); U. Colorado (Dr. A. Moore); SIO (Dr. A. Miller); IMGA, Modena, Italy (Dr. N. Pinardi) and the Naval Postgraduate School (Dr. Ching Sang Chiu).

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